Comparison of hydrography and circulation on the Newfoundland Shelf during 1990–1993 with the long-term mean

E. Colbourne, Brad deYoung, S. Narayanan, and J. Helbig

Abstract: Meteorological and ice data from the Atlantic region indicate that the large-scale atmospheric circulation over the Northwest Atlantic during the early 1990s caused below-normal air temperatures in eastern Canada, resulting in increased ice growth during winter, increased ice transport from northern latitudes, and increased freshwater from melting ice during spring. The reduced solar flux onto the ocean surface resulted in a 3- to 4-wk delay in the annual warming cycle causing record low temperatures over the upper water column throughout the Newfoundland Shelf region. We examined temperature, salinity, and current measurements from acoustic Doppler current profilers, moored current meters, and drogued drifting buoys to establish the hydrographic conditions and circulation on the Newfoundland Shelf during 1990–1993 in relation to the longer term (1950–1989) mean. The mean circulation and transport do not show significant departures from the long-term average, but the total advective summer heat transport through the Bonavista transect indicates a 26% reduction during the early 1990s.

Résumé : Les données relatives aux conditions météorologiques et à la couverture de glace pour la région de l'Atlantique indiquent que la circulation atmosphérique à grande échelle au-dessus de l'Atlantique Nord-Ouest dans les premières années de la présente décennie a causé, dans l'Est du Canada, des températures de l'air inférieures à la normale, ce qui a entraîné une augmentation de l'englacement durant l'hiver, un accroissement du transport de glace à partir des latitudes nordiques, et une augmentation de la quantité d'eau douce provenant de la fonte des glaces au printemps. La réduction du flux solaire atteignant la surface de l'océan a entraîné un retard de 3 à 4 sem dans le cycle annuel de réchauffement, ce qui a occasionné des records de basse température de l'eau de surface, dans toute la région de la plate-forme de Terre-Neuve. Nous avons étudié les mesures de la température, de la salinité et des courants obtenues grâce à des profileurs de courant acoustiques Doppler, à des courantomètres mouillés et à des bouées dérivantes équipées de drogues, afin de déterminer les conditions hydrographiques et la circulation sur la plate-forme de Terre-Neuve au cours des années 1990–1993 par rapport aux valeurs moyennes établies sur de plus longues périodes (1950–1989). Les moyennes pour la circulation et le transport ne montrent pas d'écarts significatifs par rapport à la moyenne sur 49 ans; par contre, le transport total de chaleur par advection en été sur la section de Bonavista indique une réduction de 26% au début des années 90.

[Traduit par la Rédaction]

Introduction

The oceanographic climate on the continental shelf off eastern Newfoundland and Labrador is mainly determined by the Labrador Current, which transports cold, relatively fresh, polar water together with sea ice and icebergs from the arctic to lower latitudes along the Labrador, Northeast Newfoundland Shelf, and Grand Bank regions (Fig. 1). These arctic waters can be traced as far south as the Middle Atlantic Bight (Chapman and Beardsley 1989; and Mertz et al. 1993). The current system, which itself comprises only a small part of the circulation in the Northwest Atlantic, is formed near Cape Chidley Labrador and is fed by arctic water from the eastern arctic through Davis Strait and from Hudson's Bay and the Arctic Archipelago through Hudson Strait, reaching the Grand Bank area about 3–6 mo later (Fig. 2). The oceanic properties of the Labrador Current water over the Newfoundland continental shelf are primarily determined by meteorological wind forcing and solar heat exchange of the Northwest Atlantic including the arctic regions.

It has been suggested that environmental conditions on the shelf, either temperature (deYoung and Rose 1993) or salinity (Myers et al. 1993), strongly influence the distribution and recruitment of Atlantic cod (*Gadus morhua*). In response to the recent decline in both pelagic and groundfish resources of Atlantic Canada, there has been an increased effort to determine possible linkages to changing patterns in the physical environment. Two major research initiatives, the Northern Cod Science Program (NCSP) and the Ocean Production Enhancement Network (OPEN), yielded a large amount of environmental data from 1990 to 1993, primarily on the Northeast Newfoundland Shelf from the southern Grand Bank to Hamilton Bank on the southern Labrador Shelf (Fig. 1).

Since the late 1980s the Northwest Atlantic has experienced severe meteorological, oceanographic, and ice conditions (Drinkwater et al. 1992; Narayanan et al. 1992, 1995;

Received March 17, 1995. Accepted November 30, 1995.
J13308

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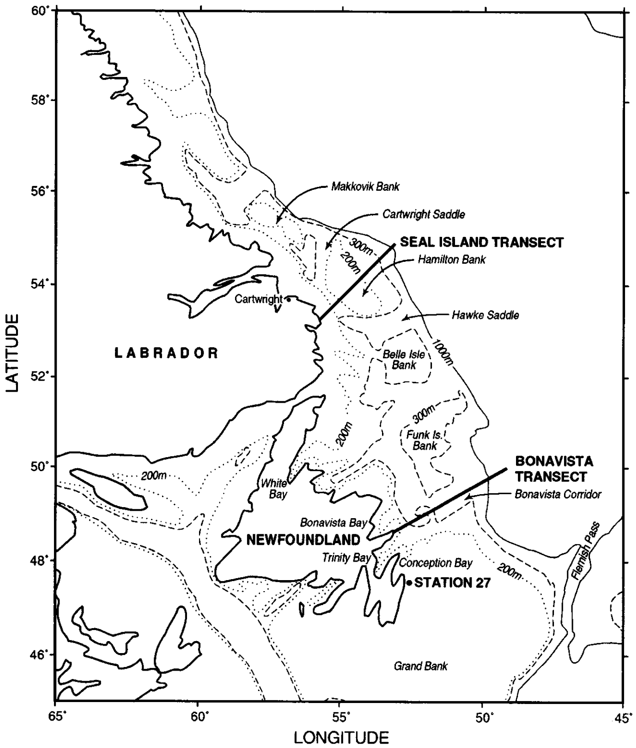
Fig. 1. Map of the study area showing the positions of the standard Bonavista and Seal Island transects and Station 27.



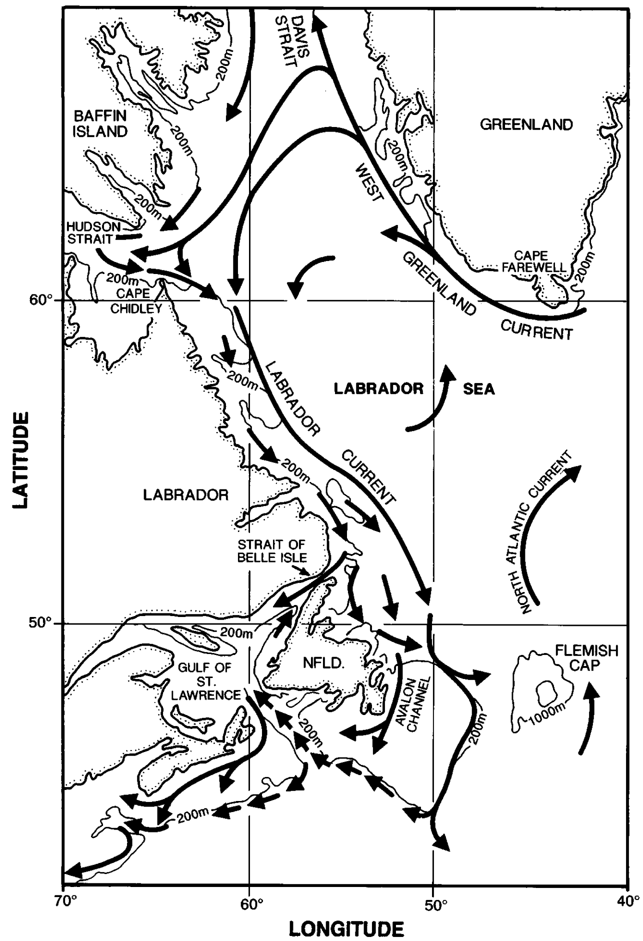
Petrie et al. 1992; Drinkwater 1993; Colbourne 1993*a*; 1993*b*). In general, the continental shelf of Newfoundland and Labrador has experienced widespread negative water temperature anomalies, with upper layer temperatures reaching a record 3.0°C below normal during the early summer of 1991. In addition, salinities were generally fresher than normal during spring and summer, particularly in the upper layers where the immediate effect of the increased ice melt is felt.

The main objective of this paper is to examine how the oceanographic conditions on the continental shelf of Newfoundland and Labrador during the early 1990s have responded to the changing weather patterns. In particular, the water property distributions with reference to the long term (1950–1989) average at Station 27 and along the Bonavista transect (Fig. 1) will be reviewed. The main circulation features of the Labrador Current determined from drifting buoys, moored current meters, and ship-mounted acoustic Doppler current meters are presented. Volume and heat transports of the Labrador Current computed from historical and the 1990s data are compared with previous estimates.

General environmental conditions

In contrast with general warming trends, 0.5°C worldwide (Jones and Wigley 1990) and 1.0°C over North America since 1900 (Saulesleja 1994), the Northwest Atlantic has experienced anomalously cold meterological conditions since the late 1980s (Findlay and Deptuch-Stapf 1991). This is a direct result of the large-scale pressure fields over the North Atlantic. A near stationary winter low pressure system centered over Iceland and a high pressure system centered over the Azores are the dominant features (Fig. 3*a*). When the Icelandic low forms during the winter months the atmospheric circulation over the region is generally from the northwest, pumping cool arctic air over large areas of the Northwest Atlantic Ocean and eastern Canada. The strength of the winter atmospheric circulation over the Northwest Atlantic is primarily influenced by the intensity of the Icelandic low which reaches its maximum during the winter months. A convenient measure of the strength of this circulation is the difference between sea level air pressure measured over the Azores and Iceland, commonly referred to as the North Atlantic Oscillation (NAO) index (Rogers 1984). Periods with high positive NAO values correspond to stronger cyclonic circulation in the North Atlantic.

Fig. 2. General circulation in the Northwest Atlantic showing major current systems (adapted from Chapman and Beardsley 1989).



During the winter months (December–February) of the early 1990s the Icelandic low was generally deeper than normal, while the atmospheric pressure over the Azores was higher than normal (Fig. 3*b*) producing a strong northwesterly circulation bringing cold arctic air to Atlantic Canada. The correlation between the 5-yr low-pass-filtered winter NAO index anomaly and the frequency of winter geostrophic winds from the northwest (315 ± 22.5°) over the Labrador Shelf is 0.75 ($p = 0.05$) (Fig. 4). As shown in the time series, particularly in the early 1990s, these circulation patterns gave rise to

Fig. 3. (*a*) Normal (1951–1980) 100 kPa surface (decametres) pressure field over the Northwest Atlantic during winter (December–February) and (*b*) the early 1990s 100 kPa surface pressure field anomalies (courtesy of Atmospheric Environment Service, Ontario, Canada).

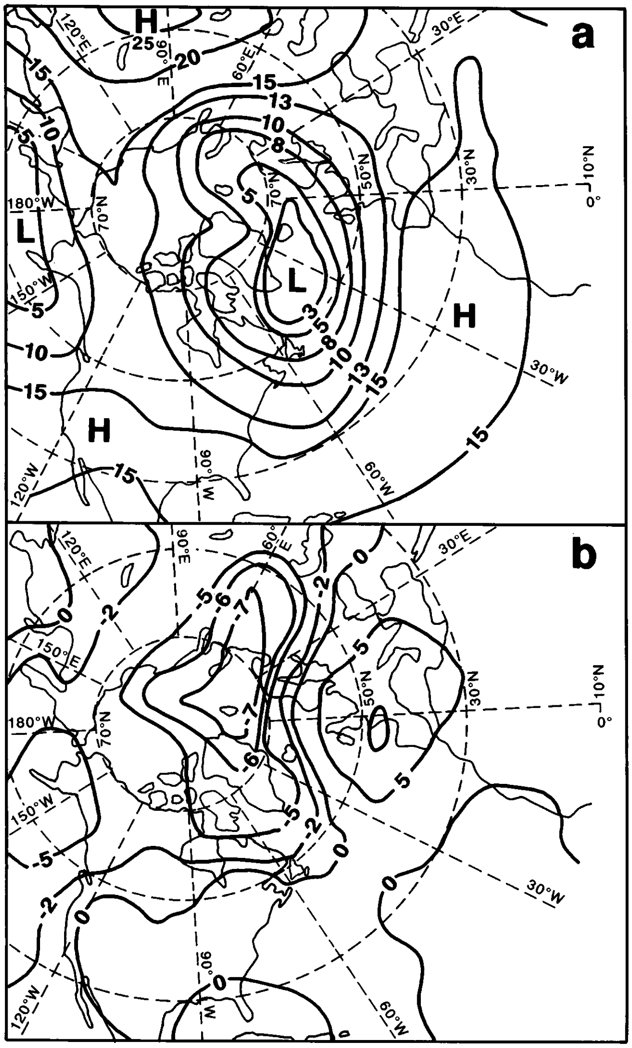
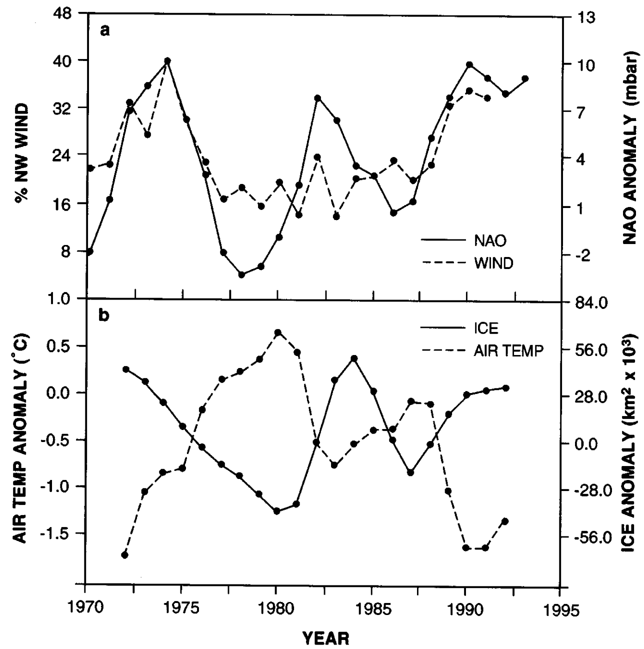


Fig. 4. Time series of the (*a*) 5-yr averaged NAO index anomaly (1 mbar = 100 Pa) and frequency of winter northwesterly winds at Cartwright, Labrador, and (*b*) air temperature anomalies at Cartwright and ice coverage anomalies over the Newfoundland Shelf between 49 and 52°N (adapted from Colbourne et al. 1994).



increased winter ice production, increased ice transport to lower latitudes, and colder than normal winter air temperatures over Atlantic Canada (Colbourne et al. 1994; Prinsenberg et al. 1997). The NAO index anomaly and Cartwright winter air temperature anomalies and the Northeast Newfoundland Shelf ice coverage anomalies are all significantly correlated (r = –0.85 and 0.72 (p = 0.05), respectively).

The oceanographic conditions on the Newfoundland Shelf have responded in phase with the meteorological and sea ice anomalies discussed above. The cross-sectional area of subzero (Celsius) water (cold intermediate layer, CIL) on the continental shelf off Cape Bonavista (Fig. 5*a*) shows an increasing trend from the early 1970s to the present, with large-amplitude fluctuations at near decadal time scales which are highly correlated with the meteorological and ice conditions (e.g., r = 0.78, p = 0.05 for CIL and ice anomalies). Similarly, the total heat content ($H/c_p\rho$) of the water column at Station 27 (Fig. 5*b*) correspondingly decreased during the same time period, again with large-amplitude fluctuations at near decadal time scales. The total heat content of the water column at Station 27 reached record lows during the early 1990s.

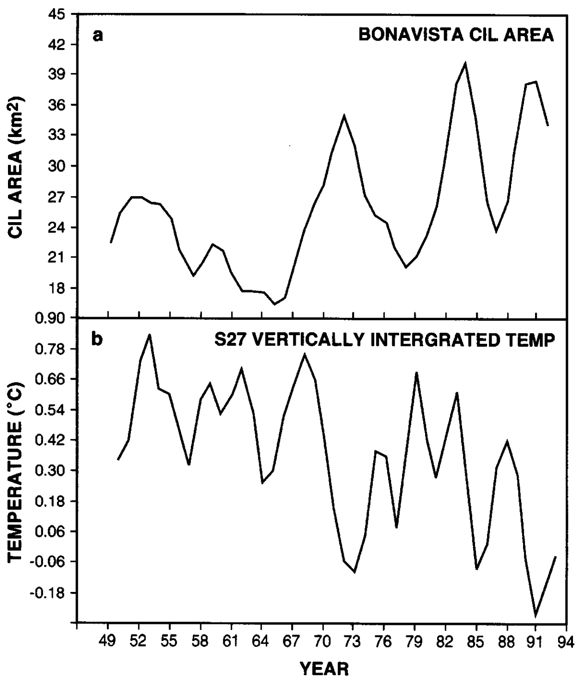
Data

Temperature and salinity

Extensive monitoring of environmental conditions on the Northeast Newfoundland Shelf was initiated under the NCSP and OPEN initiatives during the early 1990s. Vertical profiles of temperature and salinity data were collected using several different conductivity–temperature–depth (CTD) recorders including Neil Brown MKIIIB and Seabird SBE-19s, SBE-25s, and SBE-911s. Factory and frequent field calibrations maintained accuracies of 0.005°C for temperature and 0.005 for salinity. In addition, an extensive amount of historical data was available for the Newfoundland Shelf area from the Marine Environmental Data Service (MEDS) in Ottawa, Ont., Canada, and from archives at the Northwest Atlantic Fisheries Centre (NAFC) in St. John's, Nfld., Canada.

Before the late 1970s, most temperature and salinity data were collected at standard depths using water sampling bottles fitted with reversing thermometers. Since the 1960s and up to the present, a considerable amount of data was also collected using mechanical and electronic bathythermographs, but since the late 1970s, CTD recorders have been the standard. The data were quality controlled for obvious spikes, range restricted and linearly interpolated or decimated if necessary to 5.0-m depth intervals. The profiles were not extrapolated beyond their depth range.

Fig. 5. Time series of the (*a*) summer CIL cross-sectional area of water temperature less than 0.0°C from 1948 to 1993 and (*b*) Station 27 vertically (0–176 m) integrated temperature time series.



Currents

Extensive monitoring of the water currents on the Northeast Newfoundland Shelf and Hamilton Bank off southern Labrador during the early 1990s was done using satellite-tracked drifting buoys, moored current meters, and vessel-mounted acoustic Doppler current profilers (ADCPs).

Forty-nine drifting buoys were deployed on or near Hamilton Bank during the NCSP during 1991 and 1993 at various times from summer to fall near Hamilton Bank and the continental shelf in five separate clusters about 20 and 60 km in diameter. The buoys were spar shaped with a total length of 1.0 m and a maximum diameter of 0.5 m. Each buoy was fitted with a weighted 0.8-m diameter, 10-m-long holey sock drogue that was suspended between 15 and 25 m in the water column. The ratio of holey sock area to that of the buoy hull and tether was about 43:1, ensuring that the difference between the true "surface" current and the buoy speed was at most a few centimetres per second. Their positions were determined by the System Argos satellite service which provided, on average, about eight position fixes per day for each drifter.

Buoy, and hence surface, velocities were determined by fitting a B-spline to the individual observations, each of which was weighted by the estimated positional accuracy provided by System Argos. Positions and velocities were interpolated to a 3-hourly interval. These tracks were then passed through a fifth-order Butterworth lowpass filter designed to eliminate variability at temporal scales less than 24 h, thereby removing most of the tidal and inertial energy.

The ADCPs used were vessel-mounted 153.4-kHz systems manufactured by RD Instruments. These units employed four transducers mounted at 30° to the vertical and 90° in the azimuth. During all measurements, the ADCPs were operated in bottom-track mode on the continental shelf with a bin depth of 4.0 m and a sampling interval of 5.0 min, corresponding to a spatial along-track resolution of approximately 1.5 km. The number of depth bins was set to 75 corresponding to a depth range of 300 m, about the maximum useful range of the ADCP at this frequency and deep enough to reach close to bottom over most of the continental shelf. The bottom-tracking range of the 153.4-kHz system was between 500 and 600 m, depending on the sea state conditions and vessel operating speeds. Valid data were obtained from about 12 m depth to within 85% of the bottom in water depths less than 300 m and to about 300 m in water depths up to a maximum of 600 m. Data were also collected in deeper water beyond the bottom-tracking range but not included in the analysis here due to the lack of an accurate reference. The data were manually edited to remove invalid ensembles resulting from ship motion and then despiked using a threshold of 0.10 m/s on the error velocity (Colbourne et al. 1993). Invalid bins were then two-dimensionally linearly interpolated. Each transect was then filtered using a two-dimensional cosine bell filter of length 12 m vertically by approximately 5 km horizontally.

The moored current meters were Aanderaa RCM 5s and 7s and InterOcean S4s sampling at either 0.5- or 1.0-h intervals. Current meter moorings were deployed starting in the summer of 1990 and continued to 1994 in the inshore, midshelf, and the outer shelf areas in water depths ranging from 40 to 900 m (Narayanan 1994). Data recorded by these instruments included speed and direction, and, whenever possible, temperature, conductivity, and pressure. Data from approximately the same depth and location were concatenated and low-pass filtered using Godin's tide-removing filter (Godin 1972). The data were then subsampled at 6-hourly intervals. The processed time series were then used to compute statistics for the entire sampling period, including u and v components, standard deviations, and extremes.

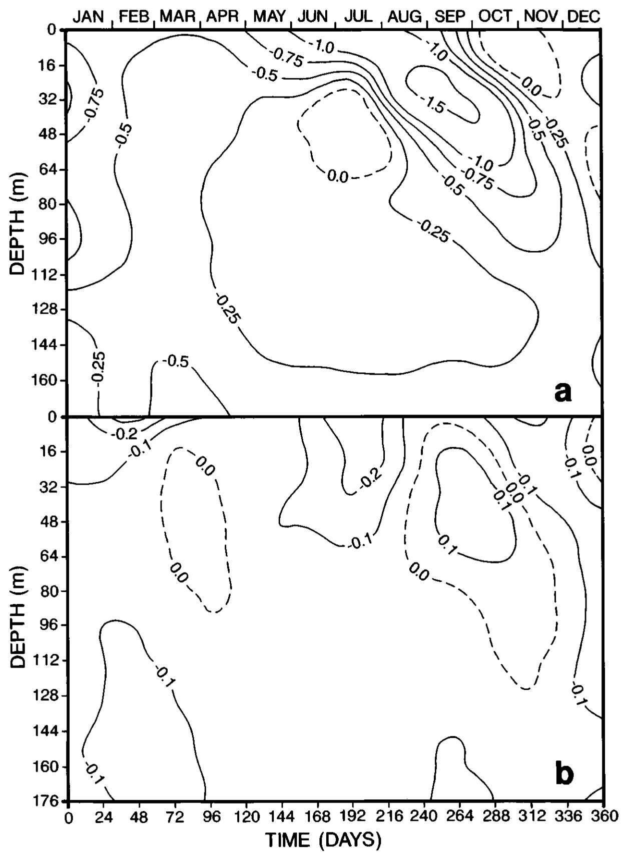
Water property distributions

Station 27

Station 27 is a standard hydrographic monitoring station in the inshore branch of the Labrador Current on the continental shelf established in 1946 (Templeman 1975). It is located about 8 km off St. John's Harbour, Newfoundland (Fig. 1), in a water depth of 176 m. This position is ideal for monitoring the inshore branch of the Labrador Current, since the cold water (<0.0°C) that forms the CIL on the continental shelf is present year-round in depths from about 100 m to the bottom at 176 m depth. In recent years, this station has been occupied on a regular basis, about two to four times per month, making it one of the most frequently monitored hydrographic stations in the Northwest Atlantic. This regular sampling permits a detailed analysis of the seasonal and interannual variability in the core of the CIL as well as the upper layer conditions on the inner Newfoundland Shelf.

As presented in Colbourne et al. (1994) and following the general methods of Smith (1983), Akenhead (1987), and Myers et al. (1990) the seasonal cycles in temperature and salinity fields were determined by fitting a least-squares regression of the form $\cos(\omega t - \phi)$ to the data. The time series of temperature and salinity anomalies presented in Colbourne et al. (1994) showed a high degree of variability, par-

Fig. 6. Monthly time series of (*a*) temperature and (*b*) salinity anomalies as a function of depth at Station 27 during the period 1990–1993 referenced to a 1950–1989 average.



ticularly in the upper water column with fluctuations of ±2.0°C and 1.0 psu at periods of about 1 yr. Variations in the anomalies near the bottom appear to have roughly a decadal time scale similar to that of the NAO index.

The vertical distribution of temperature anomalies during the early 1990s (Fig. 6*a*) referenced to the 1950–1989 mean shows winter temperatures ranging from 0.25 to 0.75°C below normal throughout the water column. The anomalies range from 0.5 to 1.5°C below normal during spring and summer in the upper water column and from 0.25 to 0.5°C below normal throughout the time period near bottom. During the early 1990s, upper layer water temperatures reached the lowest values ever recorded off St. John's (3.0°C below normal at 30 m depth during early summer of 1991), while the bottom temperature has remained below normal at about 0.5–1.0°C since 1986, the longest period since measurements began in 1946.

Similarly the vertical distribution of salinity anomalies (Fig. 6*b*) shows slightly fresher than normal conditions (generally by about 0.1–0.2 psu) in the upper water column during the winter and summer months and slightly saltier conditions during September and October due to a phase shift in the annual cycle compared with the long-term mean. Normally the salinity at Station 27 reaches its minimum during late September, corresponding to the arrival of spring ice-melt water from the Labrador Shelf (Myers et al. 1990). During the early 1990s, this was probably delayed due to the delayed spring warming.

These colder and fresher oceanographic anomalies are highly correlated with the large-scale atmospheric circulation, lower air temperatures, increased ice cover, and more frequent northwest winds, particularly during the early 1970s and 1990s and to a lesser extent the mid-1980s (Fig. 4). For example, the correlation between lower than normal air pressure over Iceland (i.e., positive NAO index anomaly) and bottom water temperature anomalies at Station 27 is –0.7 (p = 0.05).

Bonavista temperature and salinity

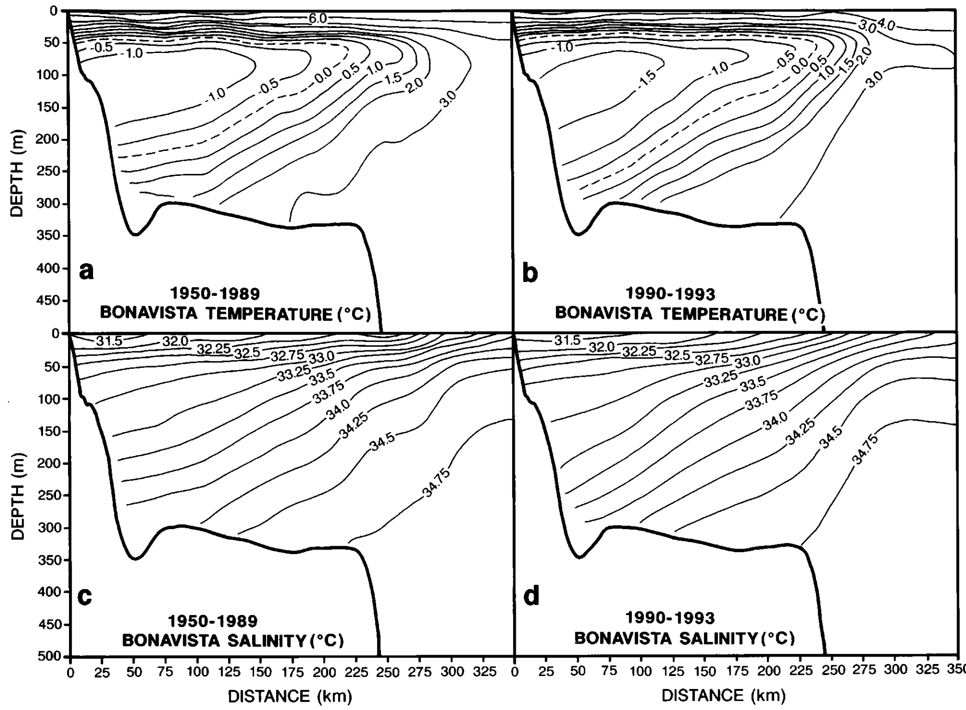
The Bonavista transect located between the Northern Grand Bank and the Southern Funk Island Bank (Fig. 1) has been occupied on a regular basis since 1950 (Colbourne and Senciall 1993). The station positions of all observations in a corridor with boundaries at ±25′ latitude along the transect, for the purposes of this analysis, were assumed to lie along a straight line with offshore distance calculated from Cape Bonavista. The data were then projected onto a 5.0-km horizontal by 5.0-m vertical grid and a simple arithmetic mean computed.

A dominant feature of the summer temperature structure on the continental shelf of eastern Canada is the large volume of subsurface water with temperatures ranging from 0.0°C to near freezing at –1.84°C, commonly referred to as the CIL (Petrie et al. 1988), and the strong temperature front separating the warmer slope water from the Labrador Current water (Narayanan et al. 1991). This feature extends from below the mixed layer at about 50 m depth to near the bottom over the outer portion of the shelf. In the winter months, the warm surface layer disappears as it cools down to near freezing temperatures due to winter cooling and strong surface mixing from winter storms. During spring and summer, ice melt and seasonal heating increase the stratification in the upper layers trapping a cold layer of water confined to the continental shelf between the warm surface water and the warmer slope water near the bottom.

The mean offshore extent of the Cape Bonavista (Fig. 7*a*) CIL for 1950–1989 was about 220 ± 44 km, centered at approximately 100 m depth with a mean thickness about 200 ± 35 m (Colbourne et al. 1994). The CIL cross-sectional area corresponding to the 1990–1993 average was 37 km^2 compared with the long-term value of 26.4 ± 8.7 km^2. In the nearshore regions during the summer months, water above 0.0°C is mainly restricted to the upper 50 m of the water column extending to less than 20 km offshore near the bottom. In deeper water, a strong across-shelf gradient (≈0.02°C/km) exists, with temperatures increasing from 0.0°C at 225 m depth to 3.0°C at the shelf break. During the early 1990s, summer temperatures in the upper layer were up to 2.0°C below average and up to 0.5°C below average in the core of the CIL (Fig. 7*b*). In addition, subzero (Celsius) water was much more extensive during the 1990s, reaching further offshore and deeper into the water column over the continental shelf.

The summer salinity (and hence density at these temperatures) structure on the shelf (Figs. 7*c* and 7*d*) shows a strong horizontal gradient indicated by the net upward displacement of the isohalines towards the offshore. The salinities during the early 1990s ranged from 0.1 to 0.2 psu below normal over the shelf as indicated by the general depression of the isohalines. Beyond the shelf break (>250 km offshore), salinities were near to slightly above normal.

Fig. 7. Vertical cross-section of the (*a* and *b*) temperature and (*c* and *d*) salinity fields along the standard Bonavista transect for the periods 1950–1989 and 1990–1993.



Continental Shelf bottom temperatures

The average near bottom temperature over most of the Northeast Newfoundland Shelf for the period 1950–1989 ranged from about –1.0 to 0.0°C inshore to greater than 3.0°C at the shelf break in water depths of 500 m or more (Fig. 8*a*). The average temperature over most of the Grand Bank ranged from less than –0.5 to 3.0°C at the edge of the bank. In general, bottom temperatures on the continental shelf are strongly influenced by the local bathymetry, with isotherms exhibiting mainly east–west gradients over most areas (Colbourne and Foote 1994; deYoung et al. 1994). These maps were constructed by contouring the temperature value at the bottom of each profile for each time period. If the bottom of the profile was not within 90% of the total water depth the profile was rejected from the analysis.

The bottom temperatures during the early 1990s have been significantly below average over the entire area. For example, the percentage area of sub-zero (Celsius) water on the Grand Bank during the period 1990–1993 was significantly larger than the 1950–1989 average (Fig. 8*b*). In general, during the early 1990s the bottom temperatures over most of the Grand Bank ranged from 0.25 to 1.0°C below the 1950–1989 average. In water depths greater than 200 m, bottom temperatures have been near normal throughout the region.

Labrador Current

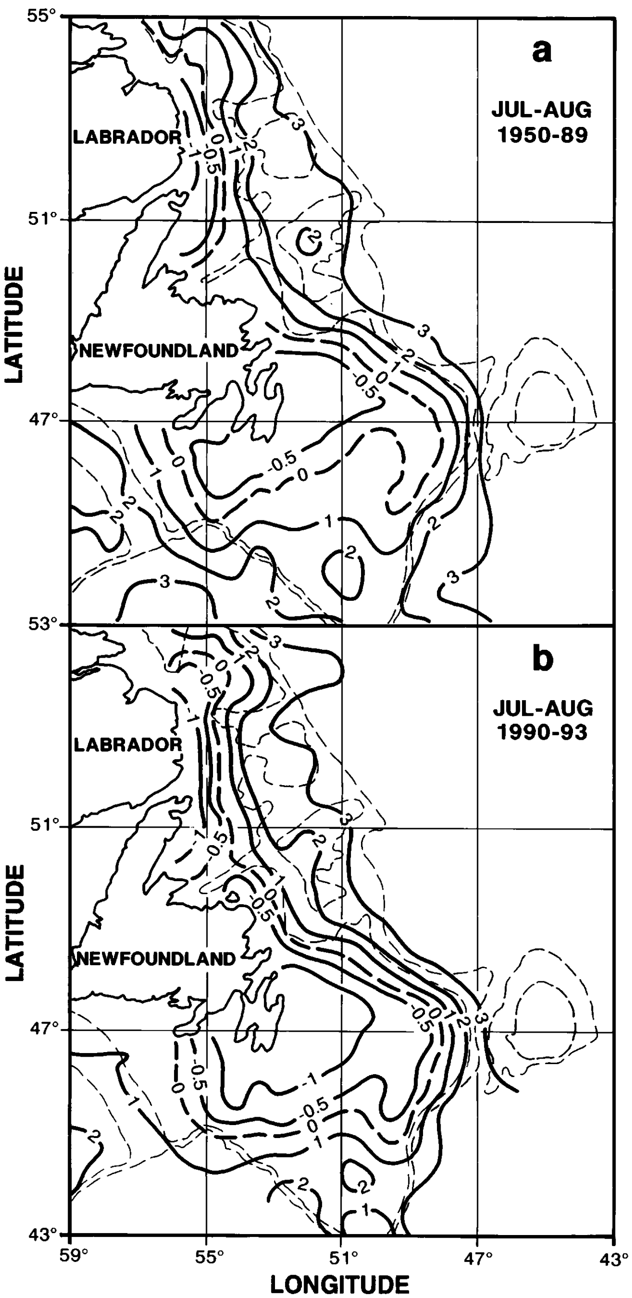
General circulation

The circulation in the Northwest Atlantic (Fig. 2) has been described many times (Smith et al. 1937; Peterson 1987; Greenberg and Petrie 1988; Lazier and Wright 1993; Petrie and Anderson 1983). It consists of the west Greenland Current which flows around Cape Farewell and up the west coast of Greenland, a branch of which turns and crosses the northern Labrador Sea forming the northern section of the Northwest Atlantic subpolar gyre. Near Cape Chidley, outflow through Hudson Strait combines with the east Baffin Island Current and a part of the west Greenland Current to form the western section of the gyre. This current then flows down the Labrador coast as a strong western boundary current known as the Labrador Current. A component of the current follows the various cross-shelf saddles on the Labrador coast forming a well-defined inshore branch by the time the current reaches Hamilton Bank with average speeds of approximately 0.15 m/s carrying about 15% of the total transport. Most of the flow remains bathymetrically trapped at the edge of the continental shelf with average speeds of approximately 0.40 m/s carrying about 85% of the total transport mainly between the 400- and 1200-m isobaths (Lazier and Wright 1993). Further south, near the northern Grand Bank, the inshore branch becomes broader and less defined with most of the transport combining with the offshore branch and a part which flows through the Avalon Channel around the Avalon Peninsula westward along the Newfoundland south coast. The offshore branch flows around the tail of the Grand Bank westward along the continental slope, where it is influenced by the Gulf Stream and slope waters, to the Laurentian Channel and into the Gulf of St. Lawrence (Hachey et al. 1954). Additionally, part of the flow combines with the North Atlantic Current and forms the southern section of the subpolar gyre.

Velocities, mean flows, and transport

The Labrador Current consists of a baroclinic component as well as a barotropic component. The relative baroclinic component perpendicular to a transect can be calculated from the density field determined by temperature salinity and pressure

Fig. 8. Summer (July–August) continental shelf horizontal bottom temperature maps for the 1950–1989 (*a*) and (*b*) 1990–1993 averages.



measurements, assuming a balance between the Coriolis force and the horizontal pressure gradient. The total current, baroclinic plus barotropic, can be measured using moored current meter arrays, ship-mounted ADCPs, and satellite-tracked Lagrangian drifters.

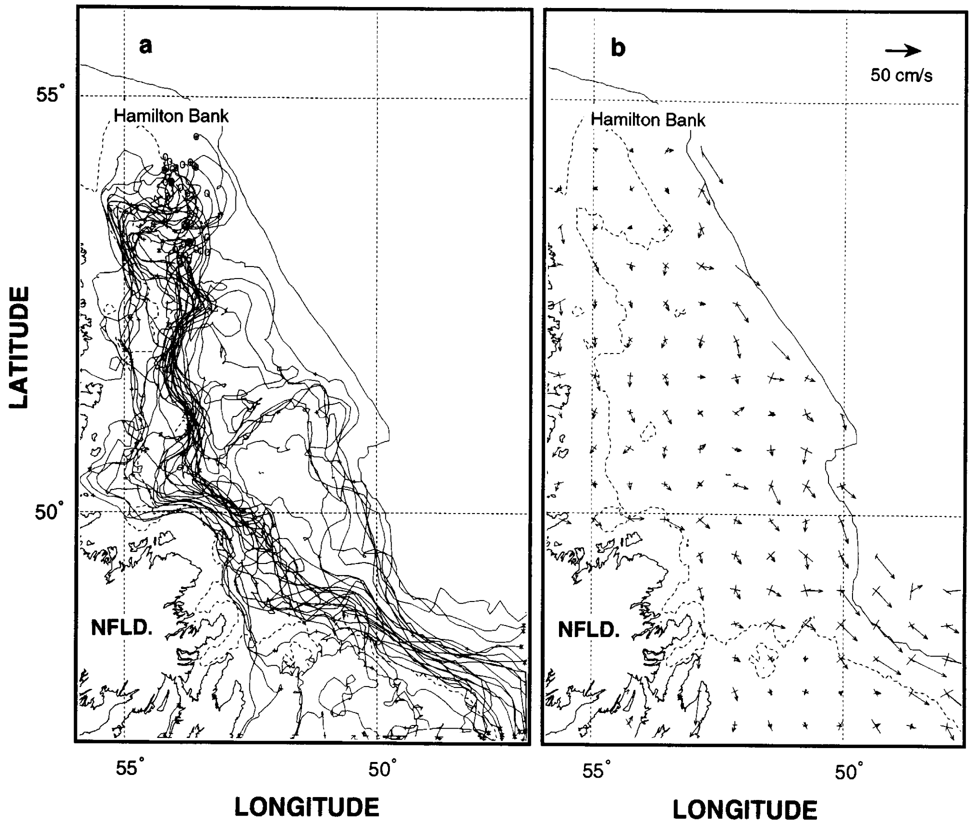
Drifter, ADCP, and current meter observations

The 49 drifting buoy tracks were used to derive a mean upper layer flow field for the Northeast Newfoundland Shelf. All buoys were deployed inshore of the 600-m isobath in an effort to avoid the offshore branch of the Labrador Current, since these drifter deployments were designed to simulate the drift of fish eggs and larvae on the shelf. The buoys generally moved in a southerly direction and displayed a remarkably consistent drift onshore through Hawke Saddle south of Hamilton Bank (Fig. 1) and remained over the shelf until they joined the offshore branch of the Labrador Current along the northern edge of the Grand Banks through the Bonavista Corridor (Fig. 9*a*). The buoys also tended to sample certain regions preferentially: areas where currents diverge were undersampled whereas buoys tended to cluster in convergence zones. Also noteworthy are the few buoys that grounded inshore as well as those (six) that drifted onto the northern Grand Bank or into the inshore branch of the Labrador Current. A significant portion of the buoys released on Hamilton Bank followed the broad inshore branch of the Labrador Current over the Northeast Newfoundland Shelf until most were bathymetrically funnelled offshore through the Bonavista Corridor (Fig. 1) where they were entrained in the offshore branch. The small number that arrived on the Grand Bank indicates that the inshore branch is very broad and weak south of the Bonavista transect with the exception of some nearshore intensification through the Avalon Channel. Thus the retention of ichthyoplankton on the Grand Bank may be less influenced by the Labrador Current than elsewhere on the Newfoundland Shelf considering the longer residence time of Grand Bank waters (Helbig et al. 1992).

To produce the velocity field from the drifting buoys, the data were spatially binned into 50-km squares and then a track-length weighted average was produced. Where currents are relatively strong, the mean velocities tend to be large compared with fluctuations, but over the shelf, where mean currents are relatively weak, fluctuations and mean velocities are of similar magnitude (Fig. 9*b*). To compare the means and standard deviations of the currents derived from the drifting buoys with the moored instruments, we extracted the current vectors corresponding to those bins that contain a current meter mooring, which was typically at 40 m depth. In general, the drifting-buoy-derived near-surface currents are similar in direction to those monitored at 40 m by the fixed current meters (Fig. 10), but the fluctuations are considerably more energetic, with standard deviations often larger than the means (Table 1). This is not unexpected, since a drogue at 15–25 m depth will experience high-frequency surface effects stronger than at 40 m depth. The average magnitude of the currents derived from drifter tracks over the depth range of 15–25 m is 0.175 m/s compared with 0.102 m/s from the current meters at 40 m depth, a ratio of 1.7. This is consistent with the ratio of the International Ice Patrol (IIP) composite of all available upper layer current information to subsurface current meter measurements at 40 m depth (Narayanan et al. 1996). In general, these results show a strong offshore branch of the Labrador Current with low variability, while the currents over the banks tend to be weaker with high variability. Most of the variability over the shelf occurs in the weather band (≈2–10 d) (Narayanan 1994; Fissel and Lemon 1991) from wind-driven circulation due to storms and eddies at internal Rosby radius scales (≈10 km on the shelf).

Current measurements made along transects from moving vessels using ADCPs include the high- frequency weather band components, eddies, and tides. The removal of tides from ADCP data collected on moving platforms is difficult.

Fig. 9. (*a*) Low-pass-filtered drifting buoy tracks. Drop locations are indicated by circles and terminal positions by asterisks. (*b*) Spatially binned mean surface currents derived from spatial averages of all drifting buoy tracks. The principal axes of variation are indicated by crosses.



Unlike time series of current measurements obtained from fixed sites, ADCP measurements obtained from moving platforms do not lend themselves to a simple harmonic analysis, since the amplitude and phase of the tidal components vary spatially along the transect. In an attempt to approximate the mean flow from our ADCP measurements, we averaged the along-shelf (–30° from north) components from about 40 transects. These measurements were made along the east coast of Newfoundland on more than a dozen surveys at various times from May to November from 1991 to 1993 within about 30′ latitude of the standard Bonavista transect (Fig. 1). The current field revealed by these data does not show distinct inshore and offshore branches of the Labrador Current but rather a continuously increasing current speed from 0.05 to 0.10 m/s nearshore to over 0.20 m/s at the shelf edge (Fig. 11). The high-frequency variability has been smoothed by the averaging procedure. There is close agreement between the fixed current meter and average ADCP measurements in the offshore and midshelf areas, but the two differ by a factor of 2 nearshore in the upper 100 m of the water column. In this region the fixed current meter measurements are higher than the averaged ADCP measurements. It should be noted that the averaging periods for the two data sets do not correspond exactly.

Geostrophic circulation and transport

The historical (1950–1989) and recent (1990–1993) summer (July and August) temperature and salinity data along the Seal Island and Bonavista transects (Fig. 1) were averaged into 5.0 km by 5.0 m bins as described above and used to calculate the steric height along each transect from (Gill 1982)

$$\Phi = \int_0^p \delta \, dp$$

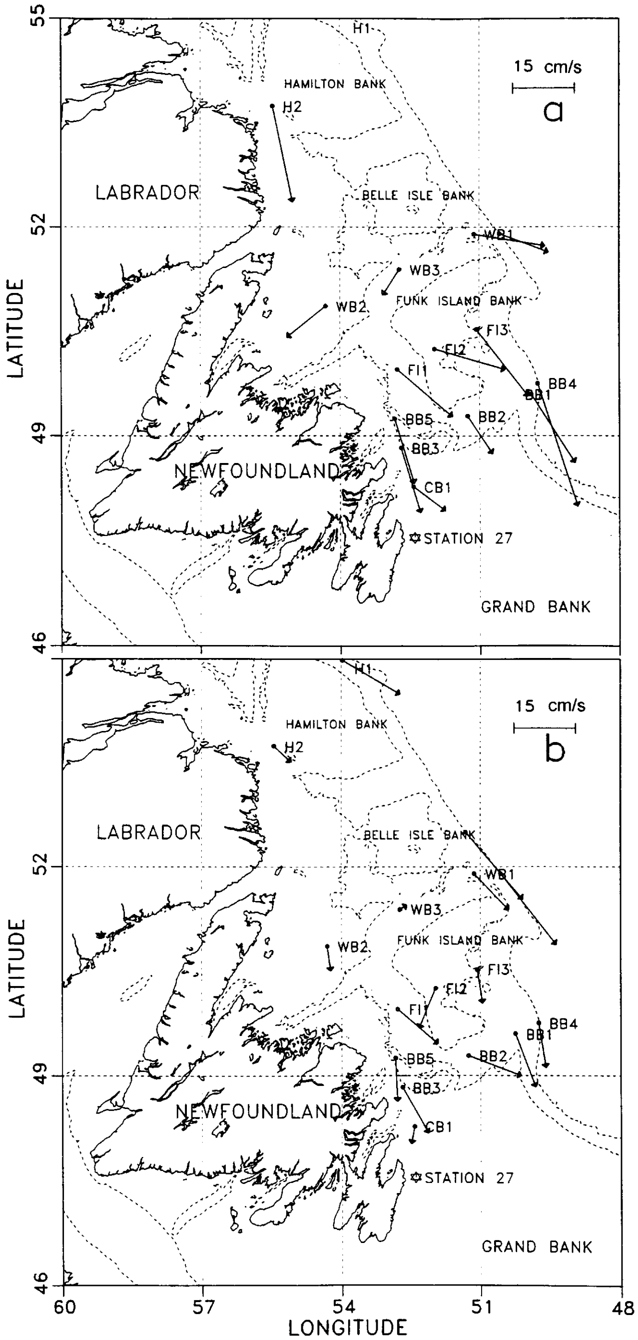
where p is the pressure or depth and δ is the specific volume anomaly given by

$$\delta = \alpha(s, t, p) - \alpha(35, 0, p)$$

and $\alpha = \rho^{-1}$. The geostrophic velocity between adjacent horizontal bins is then calculated from the horizontal gradient of Φ using the geostrophic balance relationship. Calculating the geostrophic velocity from the average density field for the two time periods rather than from individual density profiles for each year will produce a smoothed velocity field, but the transport will be representative of the average conditions.

The geostrophic currents relative to 500-m along the Seal Island transect for the two averaging periods show a weak inshore branch within 100 km from the shore and a much stronger offshore branch about 100 km wide centered at about 220 km offshore over the 500-m isobath (Figs. 12*a* and 12*b*). In the offshore branch, current speeds range from 0.05 m/s at 200 m depth to greater than 0.30 m/s in the upper 30 m of the water column near the edge of the continental shelf. In the inshore branch, current speeds are generally less than 0.10 m/s and near 0.0 m/s over midshelf on Hamilton Bank.

Fig. 10. (*a*) Near surface current vectors derived from the drifting buoys at the mooring locations and (*b*) average current vectors from the top current meter.



The geostrophic currents relative to 300 m depth along the Bonavista transect for the two averaging periods reveal an offshore branch as a narrow bathymetrically trapped jet near the edge of the continental slope. The offshore feature is about 75 km wide with speeds ranging from 0.05 m/s at 200 m depth to greater than 0.30 m/s in the upper 50 m of the water column (Figs. 12*c* and 12*d*). The inshore branch along the Bonavista transect appears broad and less well defined compared with upstream conditions along the Seal Island transect, with typical current speeds less than 0.10 m/s. This is also evident in the summer density field along the standard Bonavista transect (Fig. 7) and in the Seal Island transect data (Colbourne et al. 1995).

The transport (T) for both transects was calculated by integrating vertically through the water column using a bin size of 5.0 m and horizontally in the offshore direction across the shelf using a bin size of 5.0 km from

$$T = \int_0^L \int_{-h}^0 V\,dp\,dx$$

where L is the total horizontal distance across the shelf, V is the current speed perpendicular to the transect and h is the reference level, p is the pressure or depth, and x is the cross-shelf distance.

The geostrophic transport calculated through the Seal Island transect is about 3.5 Sv (1 Sv = 10^6 m^3/s) for the 1950–1989 average and 4.2 Sv for the early 1990s compared with 3.8 Sv calculated by Lazier and Wright (1993) for the period 1978–1987, referenced to 1500 m. The geostrophic transport through the Bonavista transect is about 3.1 Sv with no significant difference between the two averaging periods. The total transport calculated from the bottom-tracked ADCP data is about 6.0 Sv. It should be noted here, however, that a significant portion of the offshore branch was not included due to the lack of a reference. Therefore, this estimate does not represent the total transport of the Labrador Current.

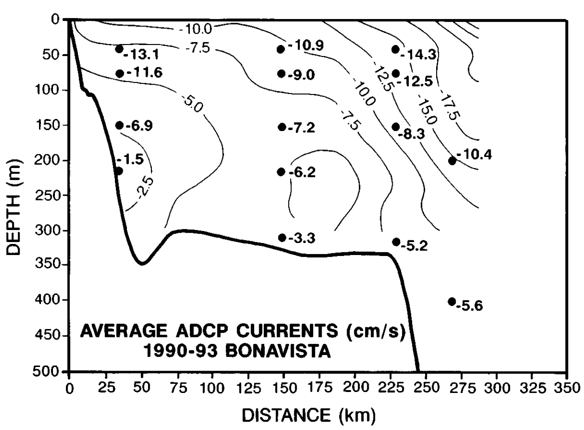
The total current field (Fig. 13) (i.e., barotropic plus baroclinic components) through the Bonavista transect for the period 1990–1993 was determined by referencing the geostrophic currents (Fig. 12*d*) to the ADCP measurements (Fig. 11) at approximately 300 m depth across the shelf. The reference currents beyond the bottom-tracking range of the ADCP (500–600 m) were linearly extrapolated based on the last several bottom-tracked ensembles. The total transport calculated from this current field is 11.9 Sv compared with 11 Sv calculated by Lazier and Wright (1993) through the Seal Island transect based on data collected from 1978 to 1987. They estimated a barotropic component of approximately 7.2 Sv from current meter measurements made close to the bottom along the 1000-m isobath at the edge of the shelf and assuming a horizontal structure for the barotropic component similar to the horizontal structure of the surface current.

The results presented here do not show significant differences in the geostrophic transport of the Labrador Current during the most recent cold period of the early 1990s compared to that for period 1950-1989. This is in contrast with the results obtained by Myers et al. (1989) who showed a significant negative correlation between the upper layer (top 100 m) geostrophic transport along the Seal Island transect and the NAO index indicating reduced transport during cold periods. In addition, Petrie and Drinkwater (1993) suggested that increased transport of Labrador Current water around the southeast Grand Bank during warm periods (mid-1960s) on the Northeast Newfoundland Shelf resulted in colder conditions on the Scotian Shelf. In our analysis, we averaged all data during the period 1950–1989 which included the two major cold periods of the early 1970s and mid-1980s (Colbourne et al. 1994); thus, we may have averaged out some interannual trends in the transport. Moreover, our geostrophic transport estimates were referenced to 300 m which may not

Table 1. Comparison of the top current meter (CMS) measurement of the *u* and *v* components and the standard deviations of the Labrador current with the estimate derived from the drifting buoys (Drifters) for the same location (see Fig. 10 for station locations).

	Position		CMS (cm/s)				Drifters (cm/s)			
Stn.	Lat.	Long.	u	σ_u	v	σ_v	u	σ_u	v	σ_v
BB1	49°36.0′	50°15.2′	5.1	4.4	−13.4	7.7	11.1	15.8	−17.5	24.6
BB2	49°17.0′	51°15.5′	13.2	7.6	−5.0	6.1	6.2	15.0	−9.3	16.5
BB3	48°50.0′	52°41.0′	6.5	8.3	−11.4	7.5	4.9	9.8	−16.4	18.0
BB4	49°45.0′	49°45.0′	1.8	1.6	−11.0	4.7	10.3	15.7	−32.0	35.6
BB5	49°15.0′	52°50.0′	0.5	8.0	−10.7	6.8	4.9	9.8	−16.4	18.8
CB1	48°16.4′	52°25.6′	−0.7	7.6	−3.7	5.8	7.8	11.3	−5.8	12.0
F11	49°57.0′	52°47.0′	10.1	5.8	−8.7	5.6	14.1	18.2	−12.0	16.2
F12	50°15.0′	51°58.0′	−4.1	4.0	−9.9	4.8	18.2	20.5	−5.3	10.1
F13	50°31.0′	51°4.0′	1.3	5.8	−8.1	7.4	13.4	19.4	−17.3	25.2
WB1	51°54.0′	51°8.0′	8.6	10.3	−9.1	6.8	18.2	22.7	−3.1	17.0
WB3	51°23.0′	52°44.0′	1.1	3.5	0.7	3.1	−3.9	11.1	−6.1	11.5
SP2	51°54.0′	50°34.0′	14.2	5.8	−18.4	7.6	12.2	14.5	−4.7	10.6
WB2	50°51.5′	54°18.5′	0.8	2.4	−5.7	6.3	−9.7	16.0	−7.8	12.6
H1	54°59.0′	53°58.7′	14.8	8.9	−8.7	5.6				
H2	53°44.5′	55°26.9′	3.9	5.6	−3.6	5.8	5.2	8.2	−25.0	25.9

Fig. 11. Average current field derived from about 40 bottom-tracked ADCP transects collected along and near the standard Bonavista transect between 1990 and 1993 with the current meter means superimposed.



be as sensitive to upper layer changes in the stratification resulting from interannual variations in the meteorological forcing as would, for example, the transport referenced to 100 m depth.

The cumulative volume transport (Fig. 14) across the shelf along the Bonavista transect increases in the offshore direction almost linearly on the shelf (within ≈200 km from Cape Bonavista), consistent with the broad inshore branch of the Labrador Current shown earlier in that area. The total transport is about 2.5 Sv within 150 km off the shore with a baroclinic component of about 1.5 Sv. This represents approximately 20% of the total transport that we calculated along this transect, not inconsistent with the generally accepted 15% for the inshore branch. There is also some indication that higher geostrophic transport occurred over the shelf during the early 1990s compared with 1950–1989, probably due to stronger horizontal density gradients caused by the increased freshwater from the melting ice cover on the continental shelf during the spring. It should be noted that the total transport computed here is that due to the portion of the Labrador Current over the continental shelf and slope regions perpendicular to the CTD transect. The flow in this region, however, has a significant cross-shelf component as indicated by the tracks from the drifting buoys (Fig. 9). Furthermore the Labrador Current is part of the much larger Northwest Atlantic subpolar cyclonic gyre which extends into the Labrador Sea with a total transport approaching ≈40 Sv (Leetmaa and Bunker 1978).

Heat transport

The temperature structure on the shelf is determined in part by the advective heat flux from upstream. In this section, we calculate and compare the total advective summer (July–August) heat transports through the Bonavista transect for the periods 1950–1989 and 1990–1993. Since no significant difference in the geostrophic transport was found between the two averaging periods, we will base these estimates on the total volume transports calculated in the previous section for the period 1990–1993, i.e., the geostrophic flow referenced to the ADCP measurements at 300 m depth (Fig. 13). By using the same velocity field for the two periods, we will only detect differences in heat transport caused by differences in the temperature field alone (Figs. 7*a* and 7*b*). Hence the differences in the heat transport due to any variability in the volume transport between the two time periods will not be detected. The heat transport (H) through a vertical cross section in watts may be approximated from (Bryan 1962)

$$H = \rho\, c_p \int_0^L \int_{-h}^0 V\, T\, dp\, dx$$

where ρ is the average density taken as 1025 kg/m^3, c_p is the average specific heat of seawater at atmospheric pressure,

Fig. 12. Vertical cross-sections of the geostrophic currents along the (*a* and *b*) standard Seal Island and (*c* and *d*) Bonavista transects for the periods 1950–1989 and 1990–1993.

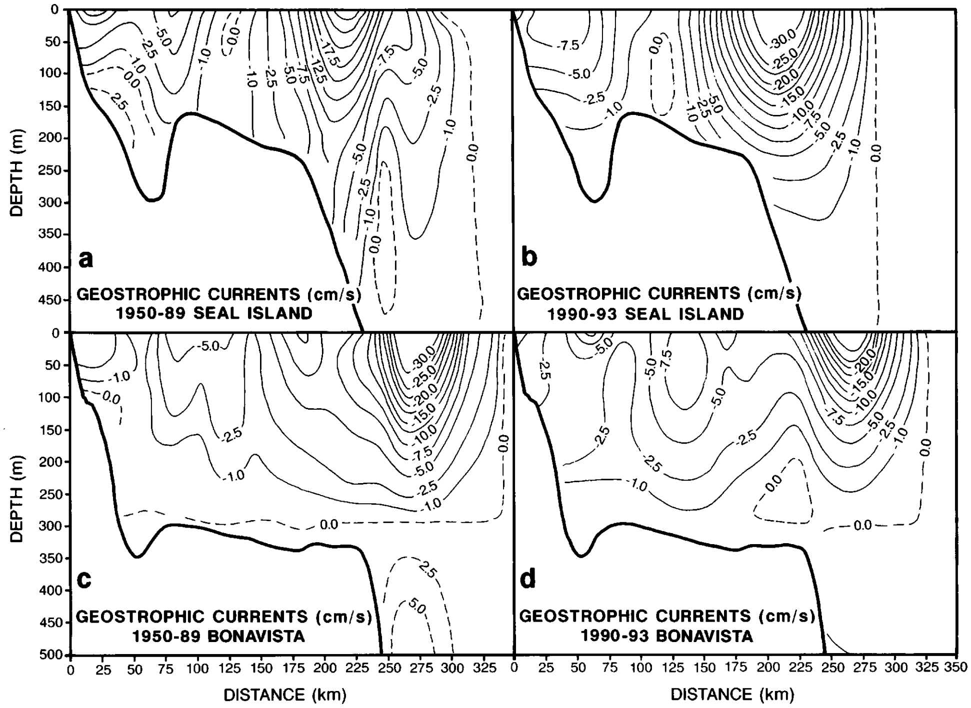


Fig. 13. Vertical cross-section of the total current field along the standard Bonavista transect for the period 1990–1993, obtained by referencing the geostrophic currents to the ADCP measurements at 300 m depth. The current meter means are superimposed.

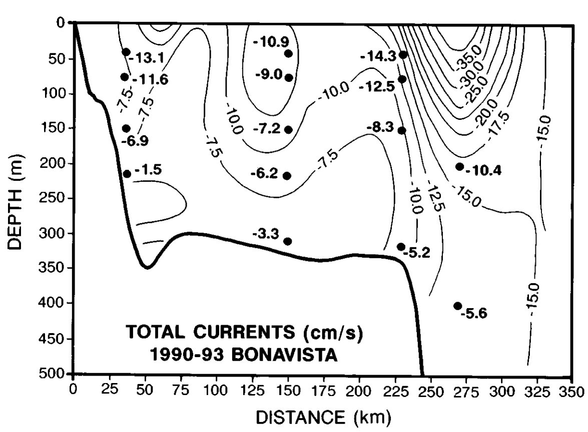
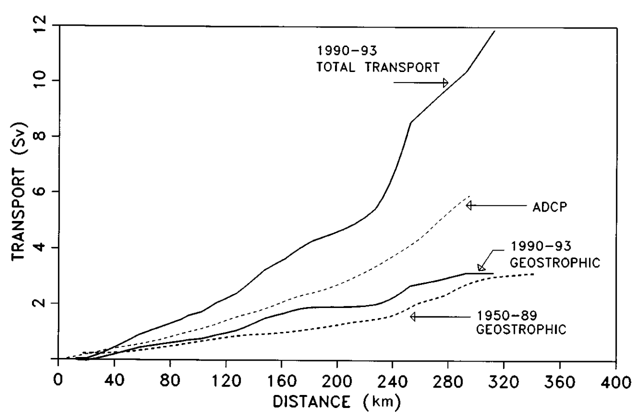


Fig. 14. Cumulative 1990–1993 total transport, 1950–1989 and 1990–1993 geostrophic transports, and the transport from the ADCP measurements along the Bonavista transect. The horizontal distance is from Cape Bonavista in the offshore direction.



about 4000 J·kg^{-1}·°C^{-1} at 0.0°C and 33.5 psu salinity (Millero et al. 1973), T is the temperature (degrees Celsius), V is the current speed in (metres per second) perpendicular to the transect, p is the pressure or depth along the transect, and x is the cross-shelf distance.

The atmosphere–ocean heat flux Q exhibits a strong annual cycle with a heat loss of the order of –75 W/m^2 during the winter months to a heat gain of over 200 W/m^2 during the summer months (Umoh et al. 1995; Mathieu and deYoung 1995). Averaged throughout the year, however, in the Newfoundland Shelf region the atmosphere supplies more heat to the ocean than it extracts, of the order of 54 – 68 W/m^2. Umoh et al. (1995) also indicated that variations in the air–sea heat fluxes can account for up to 89% of the variance in the annual water temperature cycle on the Newfoundland Shelf.

During the period 1950–1989 the total heat transport H (baroclinic and barotropic) through the Bonavista section was calculated to be 9.4×10^{13} W compared with 7.0×10^{13} W during the period 1990–1993. This corresponds to a 26% reduction during the early 1990s, which is consistent with a decrease in the heat content of the water column at Station 27 during the same period (Fig. 5*b*) and also with the meteorological and ice anomalies experienced over the Northwest Atlantic during the early 1990s (Fig. 4). When there is a net positive heat flux over the year into the ocean, then this heat has to be advected away by the local currents; otherwise the water temperature would rise. Therefore the heat flow through a cross section of the current gives some indication of the total heat flux Q from the atmosphere to the ocean over the upstream ocean surface area, since this heat is transported southward (in this area) by the currents throughout the year. The reduction in heat transport calculated here is of the same order as the low-frequency interannual variations in the total atmospheric heat flux shown by Umoh et al. (1995). This analysis suggests that much of the observed interannual variations in the ocean temperature may be explained by variations in the air–sea flux over the upstream area.

Summary

In spite of global warming trends the Northwest Atlantic has experienced below-normal air temperatures since the late 1980s. The deeper than normal low pressure system over Iceland during the winter months resulted in a stronger atmospheric circulation from the northwest bringing cold arctic air over eastern Canada and much of the Northwest Atlantic. The below-normal winter air temperatures resulted in increased ice production in northern areas and increased ice transport to lower latitudes and brought a colder and fresher water mass to the continental shelf during the spring and summer months. These anomalies reached a peak during the spring and early summer of 1991 when upper layer water temperatures fell to a record 3.0°C below normal and ice extent and duration were among the greatest and longest on record along the Newfoundland coast. Bottom temperatures over much of the continental shelf have been 0.5–1.0°C below normal since 1986, about 8 yr, the longest continuous period since measurements began in 1946.

The mean circulation determined from current measurements made during the period 1990–1993 using fixed current meters, drifting buoys, ADCPs, and calculations from density measurements compared well with previous estimates. The geostrophic transport through a transect across Hamilton Bank and off Cape Bonavista for the 1990s indicated no significant difference from that calculated from the 1950–1989 average. The current measurements made from fixed moorings along the Bonavista transect were in good agreement with the current field determined from the average of about 40 ADCP transects, except in the nearshore region where the current fluctuations were often larger than the mean flow. The total current field determined by referencing the geostrophic calculations to the ADCP measurements at 300 m depth appeared to be quite realistic; a total transport of about 11.9 Sv through the Bonavista line using these velocities was consistent with the earlier estimate of 11.0 Sv by Lazier and Wright (1993) through the Seal Island transect based on data from 1978 to 1987. Although the average transport during the early 1990s period was not significantly different from the long-term average, the differences in the temperature field alone effected a 26% reduction in the advective heat flux on the Newfoundland Shelf. These findings are consistent with the large-scale meteorological and ice anomalies experienced over the Northwest Atlantic during the early 1990s.

Acknowledgments

This work was supported through the Government of Canada's Atlantic Fisheries Adjustment Program (Northern Cod Science Program, NCSP) and the Ocean Production Enhancement Network (OPEN). We thank the many scientists who have contributed to the national data base (MEDS) over the years and the technical and computer staff at Northwest Atlantic Fisheries Centre for the professional quality of data acquisition and processing. We thank G. Mertz for reviewing this manuscript and for many useful discussions. We also thank two anonymous reviewers for many helpful comments and suggestions.

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